Limits2004
Argonne, 26-30, July, 2004

Evolution of Single-Particle Structure and Nuclear Force

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Single-particle (or shell) structure is the basis of many nuclear properties such as (sub)magic number, deformation, and even the existence of the nucleus.

The single-particle levels in exotic nuclei can be different from those of stable nuclei due to the following aspects:

- **Loose binding**
- **Neutron skin**
- ***NN* interaction, particularly, spin-isospin interactions (also in nuclei not very close to drip lines)**

Major subject :

Such shell evolution due to

tensor and 2-body *LS* interactions

Tensor Interaction

$$V_T = (\tau_1\tau_2)\left([\sigma_1\sigma_2]^{(2)}\, Y^{(2)}(\Omega) \right) Z(r)$$

contributes
only to **S=1** states

relative motion

π meson : dominant source

ρ meson (~ $\pi+\pi$) : minor cancellation for smaller *r*

Important for binding *e.g.* B.S. Pudliner et al., Phys. Rev. **C**56, 1720 (1997)

Has never shown up directly (or in the first order) in nuclear spectroscopy (e.g. levels, etc)

second-order effect on spin-orbit splitting

T. Terasawa, Prog. Theor. Phys. **23**, 87 (1960);
A. Arima and T. Terasawa, Prog. Theor. Phys. **23**, 87 (1960)

Effective single particle energy

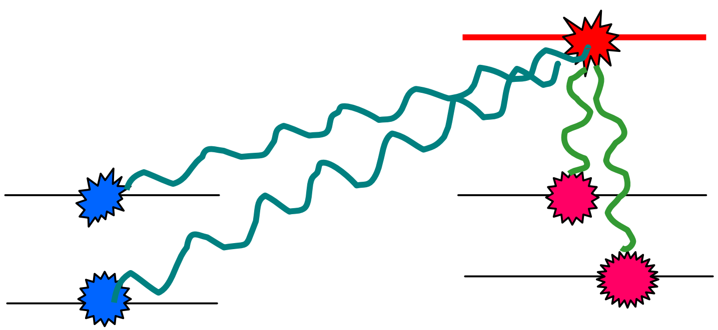
- Monopole part of the *NN* interaction

$$V_{ab}^{T} = \frac{\sum_{J} (2J+1) V_{abab}^{JT}}{\sum_{J} (2J+1)}$$

Angular averaged interaction

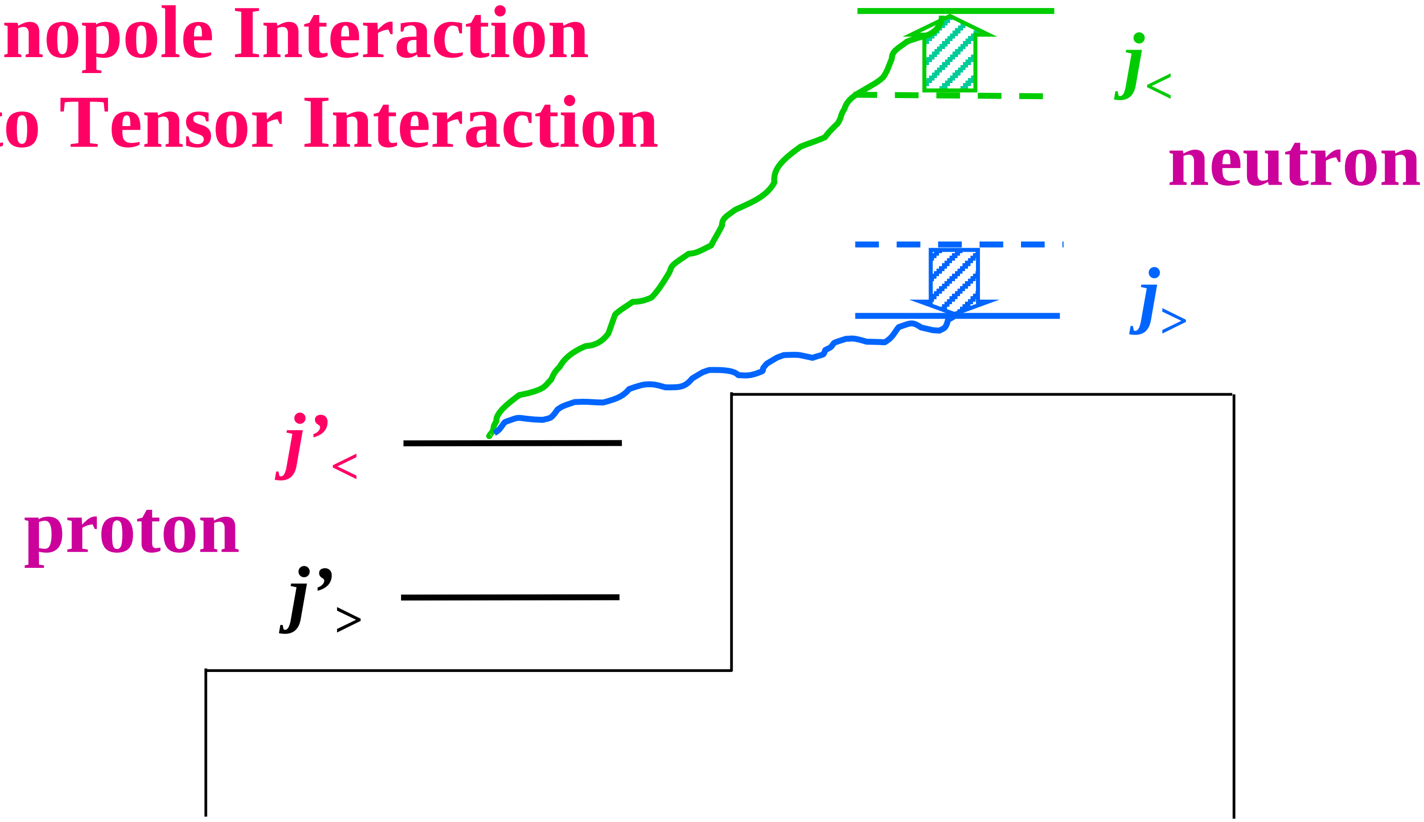
→ spherical single particle energies

- Effective single-particle energy (ESPE)



Shift of single-particle energies due to interaction with other valence nucleons

Monopole Interaction due to Tensor Interaction

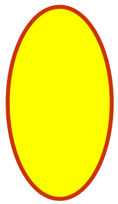


Identity

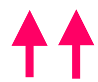
$$(2j_> + 1)\; v_{m,T}^{(j'\,j_>)} + (2j_< + 1)\; v_{m,T}^{(j'\,j_<)} = 0$$

$v_{m,T}$: monopole strength for isospin T

Intuitive Picture

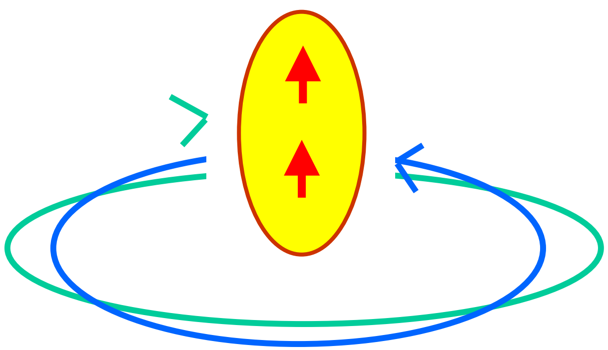


wave function of relative motion



spin of nucleon

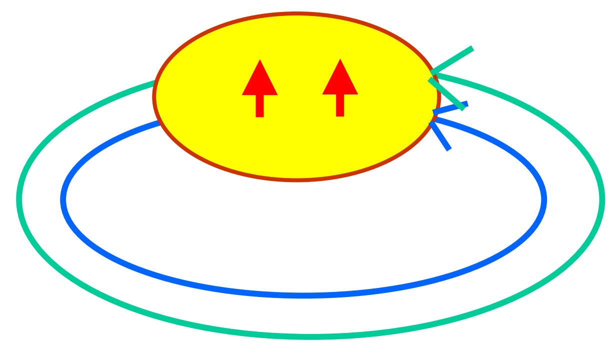
large relative momentum



$j_>$ $j'_<$

deuteron ⇨ attractive

small relative momentum

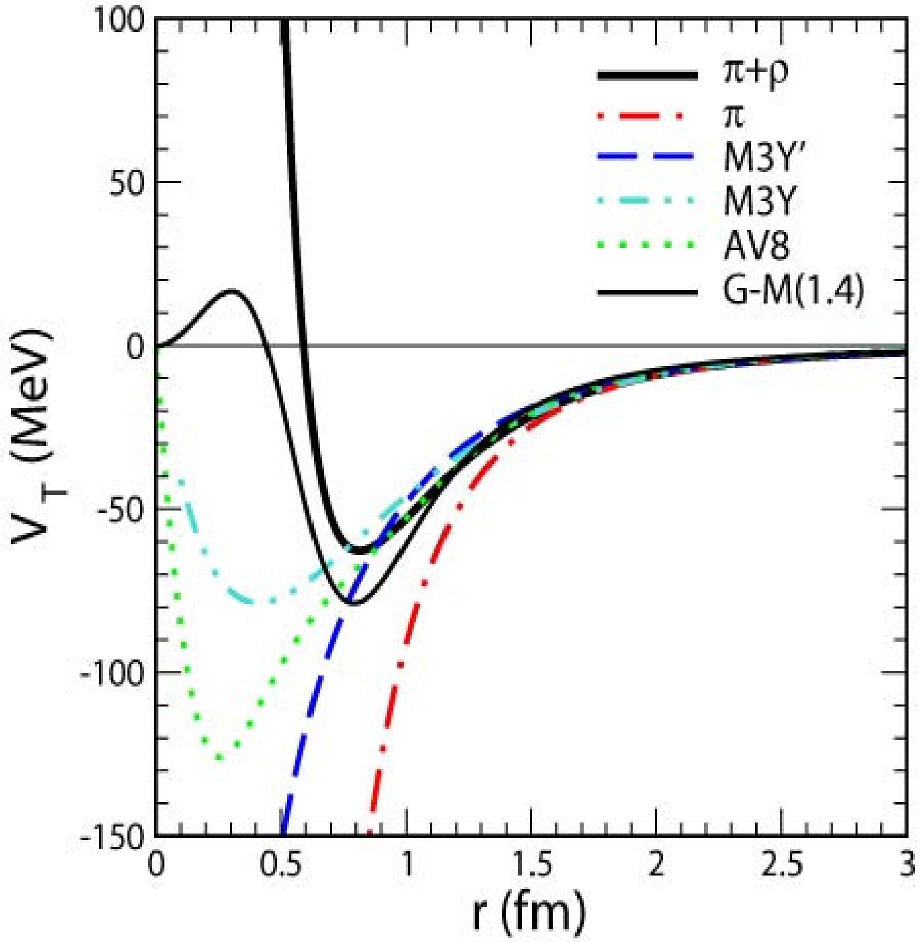


$j_>$ $j'_>$

repulsive

Effect sizable for (i) same l or (ii) large l and l'

Tensor potential

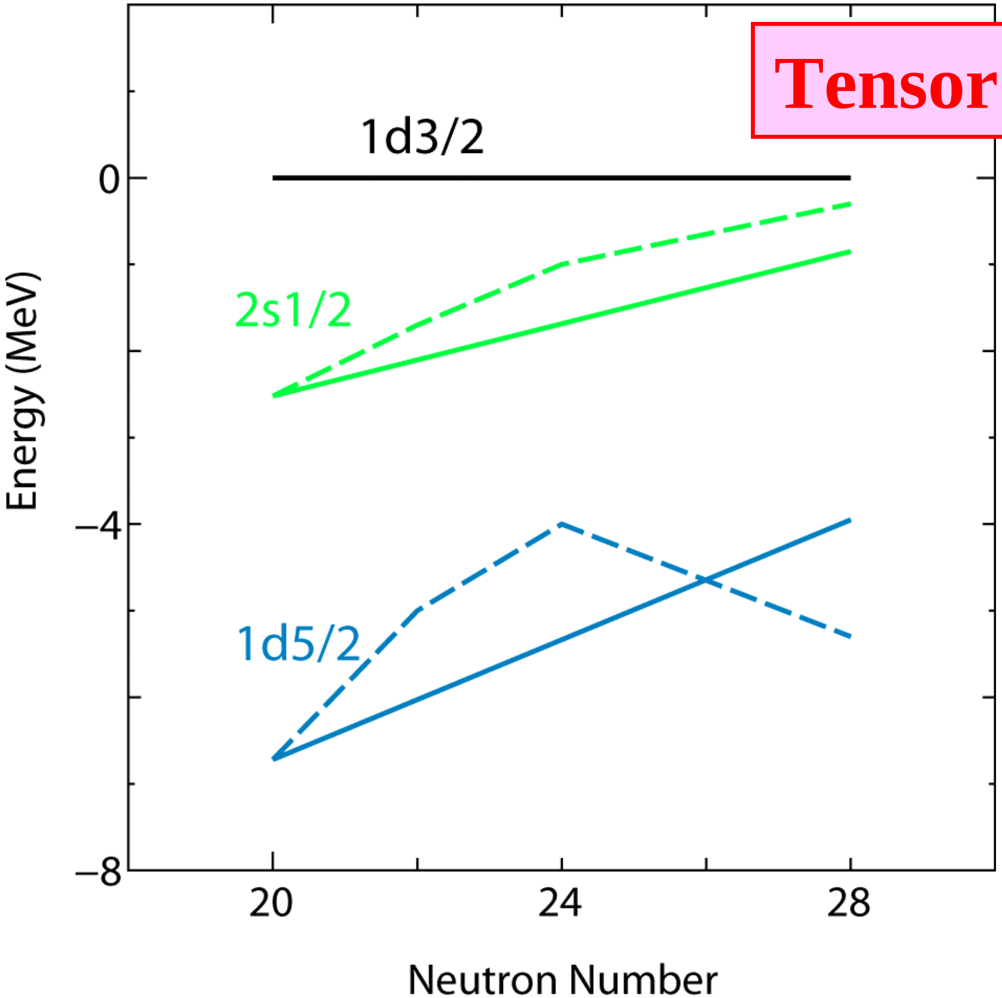


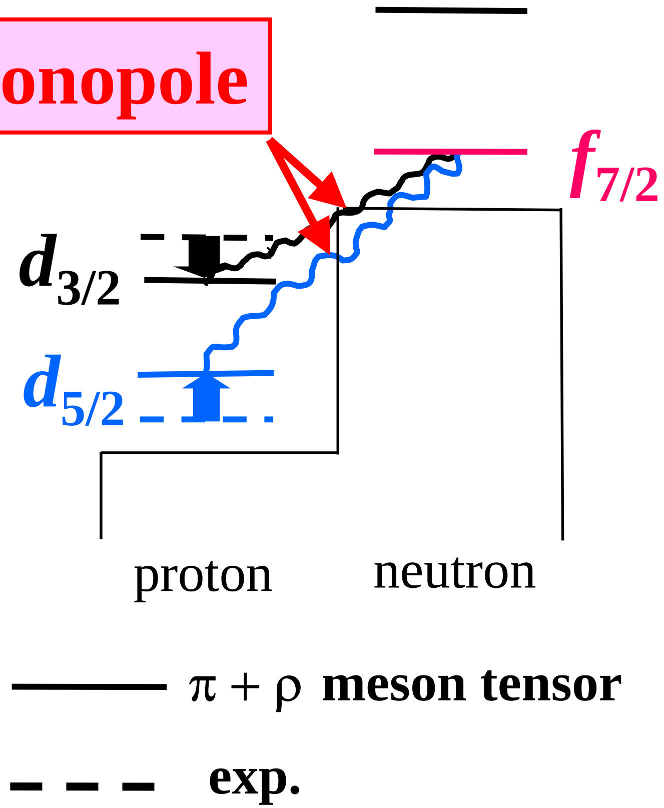
tensor

no s-wave to s-wave coupling

differences in short distance : irrelevant

Proton effective single-particle levels
(relative to $d_{3/2}$)





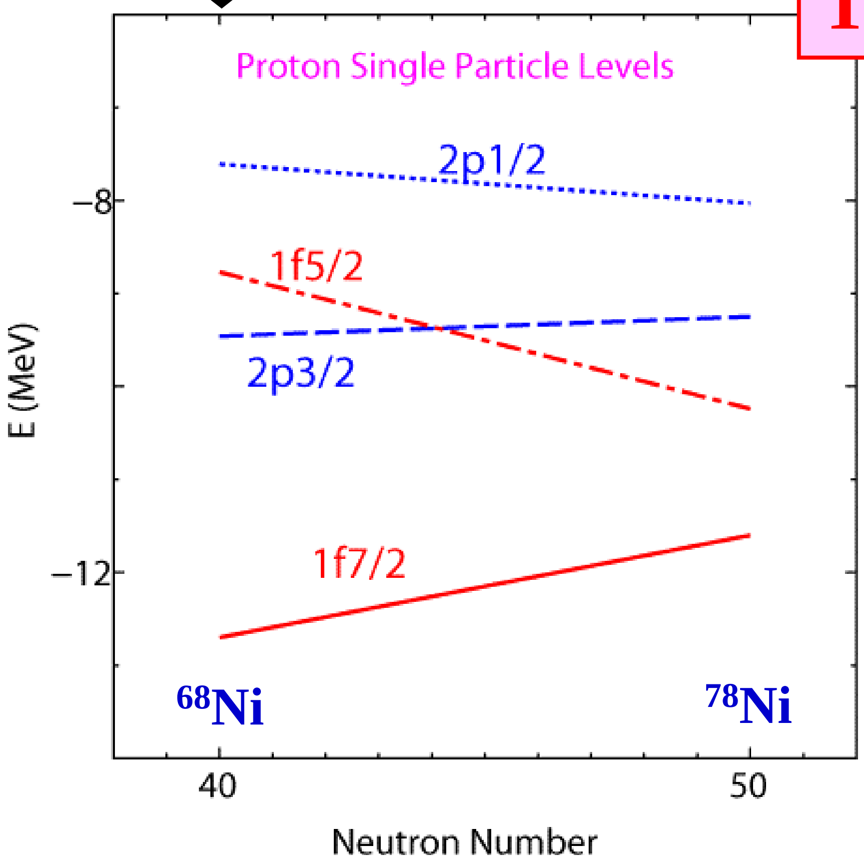
Cottle and Kemper,
Phys. Rev. C58, 3761 (98)

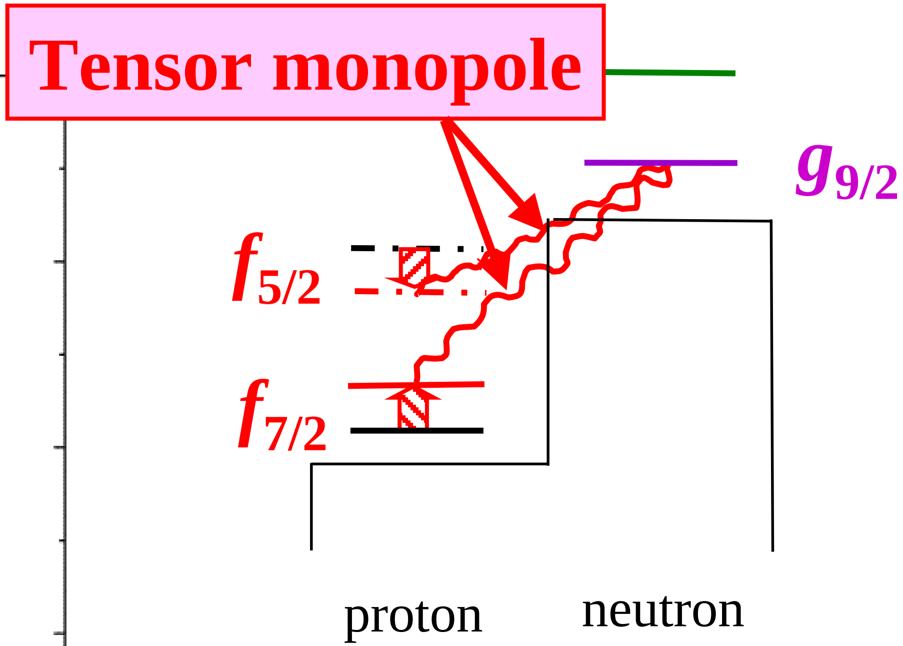
neutrons in $f_{7/2}$

Systematic variation of proton effective single-particle energies due to the tensor interaction ($\pi + \rho$ meson)

calculation only

taken from GXPF1 interaction



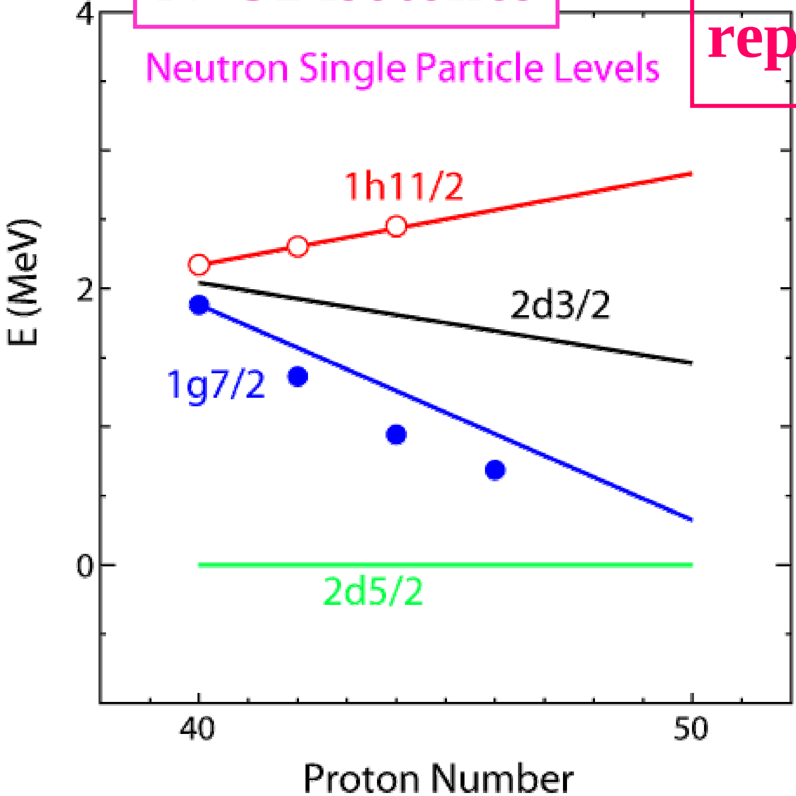


➡ Low-lying 2⁺ levels in Ni,
M. Sawicka et al.,
Phys. Rev. C68, 044304 (03)

neutrons in $g_{9/2}$

Systematic variation of neutron effective single-particle energies due to the tensor interaction ($\pi + \rho$ meson)

N=51 isotones



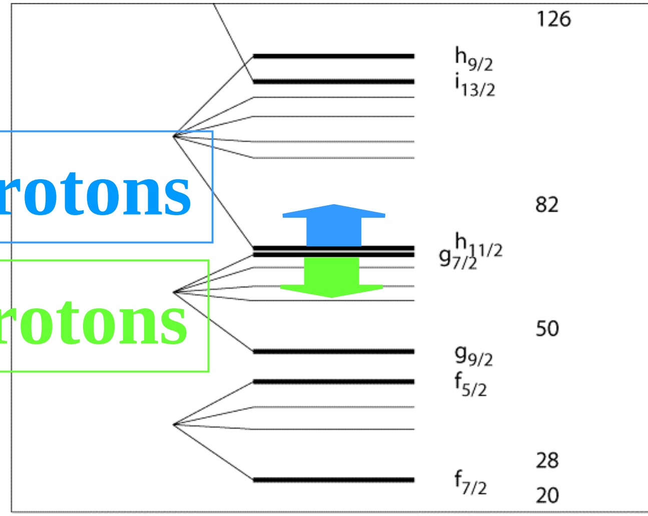
repulsion between $g_{9/2}$ and $h_{11/2}$

widening between $h_{11/2}$ and $g_{7/2}$, not spin-orbit partner

Lines : $\pi + \rho$ meson

Points : corresponding exp. level

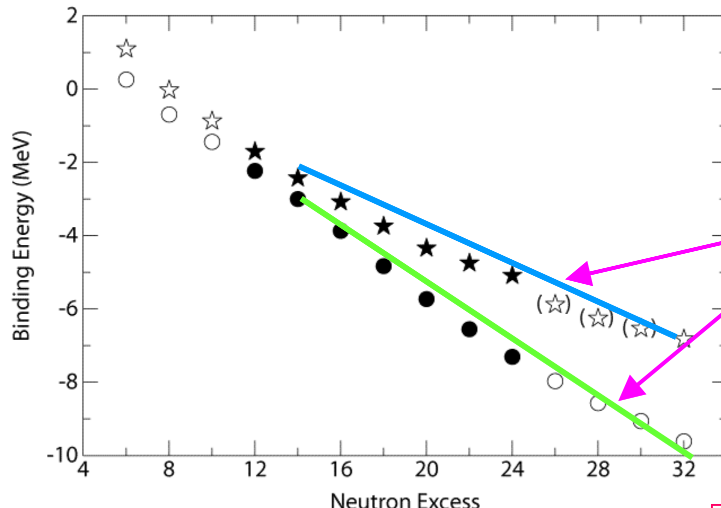
protons in $g_{9/2}$



$1h_{11/2}$ protons

$1g_{7/2}$ protons

monopole effect due to tensor interaction



$\pi + \rho$ **mesons**

+ common effect

$1h_{11/2}$ neutrons

Exp. data from J.P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004)
Also, C. Baktash, Paestum talk.

How the tensor interaction is included in effective shell model interaction ?

pf shell : GXPF1

M. Honma et al., PRC65 (2002) 061301(R)

G-matrix + polarization correction + **empirical refinement**

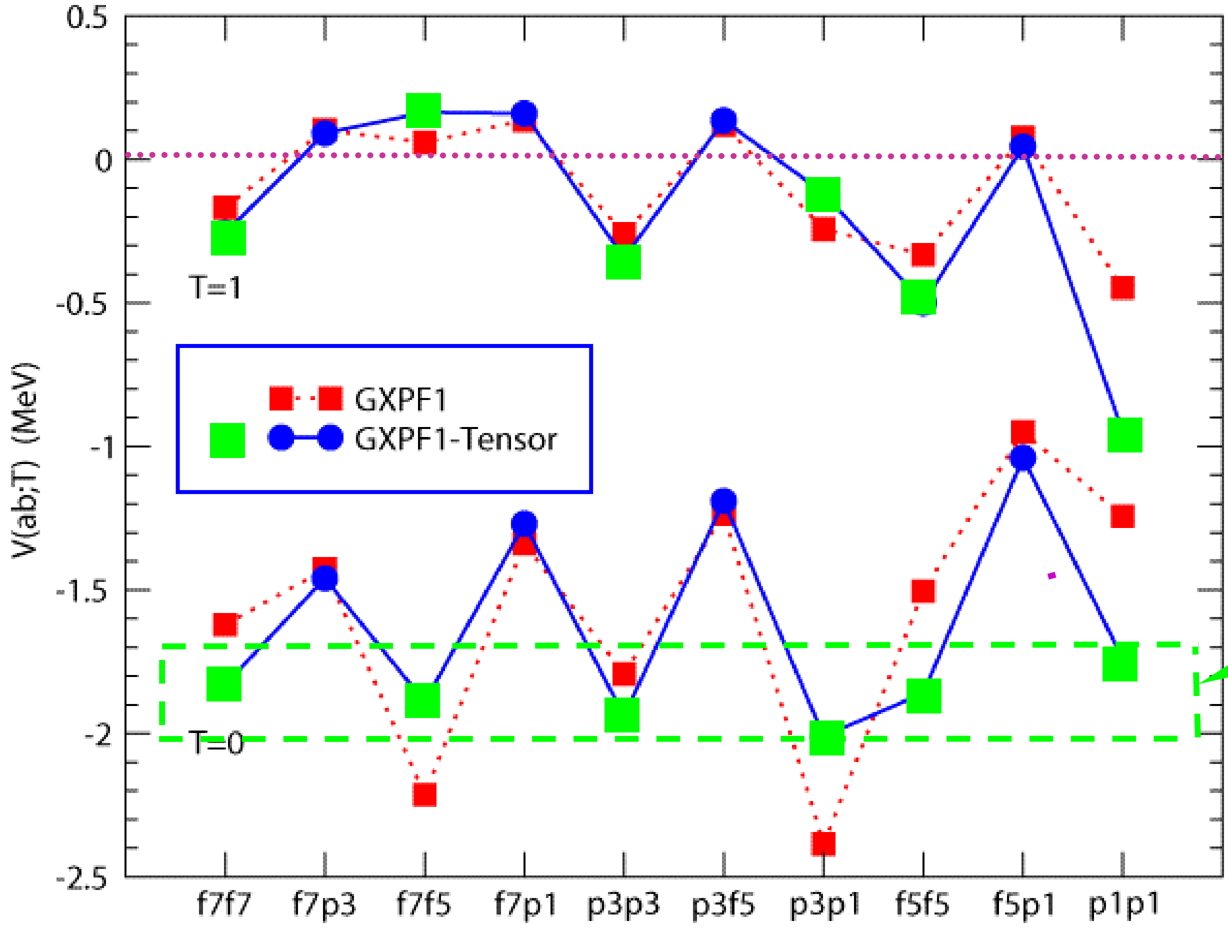
- Modify realistic G interaction

  M. Hjorth-Jensen, et al., Phys. Repts. 261 (1995) 125

  - **Bonn-C potential**
  - 3rd order Q-box + folded diagram
- Vary 70 well-determined LC's of 195 TBME and 4 SPE
- Fit to **699 experimental energy data of 87 nuclei**

Monopole interaction
after subtraction of tensor part

■ **GXPF1 - Tensor between same *l***

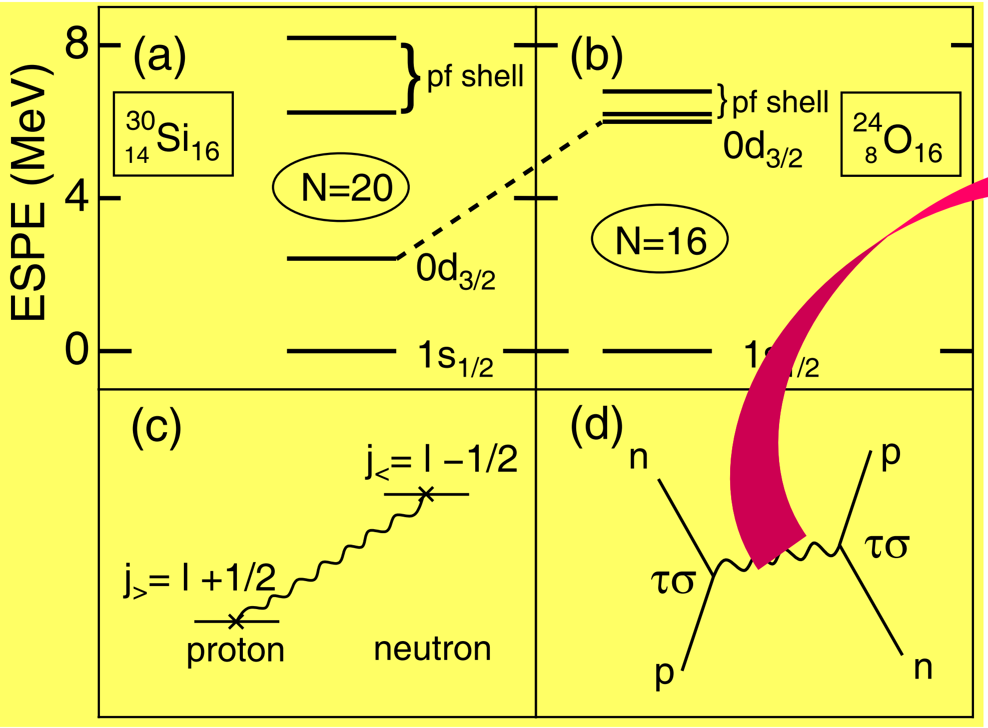


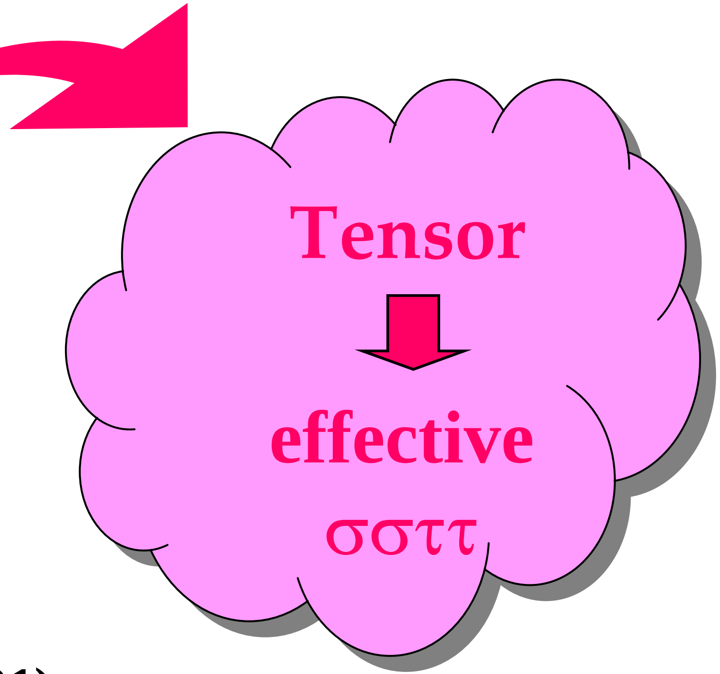
V=0

same *l*

almost constant

Tensor interaction is the primary origin of the p-n $j_>$-$j_<$ coupling also within a major shell (of a fixed parity).





Otsuka et al. Phys. Rev. Lett. 87, 082502 (2001)

Implementation of tensor interaction into mean field calculations

Gogny interaction

(1+σσ+ττ+σσττ) (Gauss1 + Gauss2) + Density Dep.

finite range **zero range**

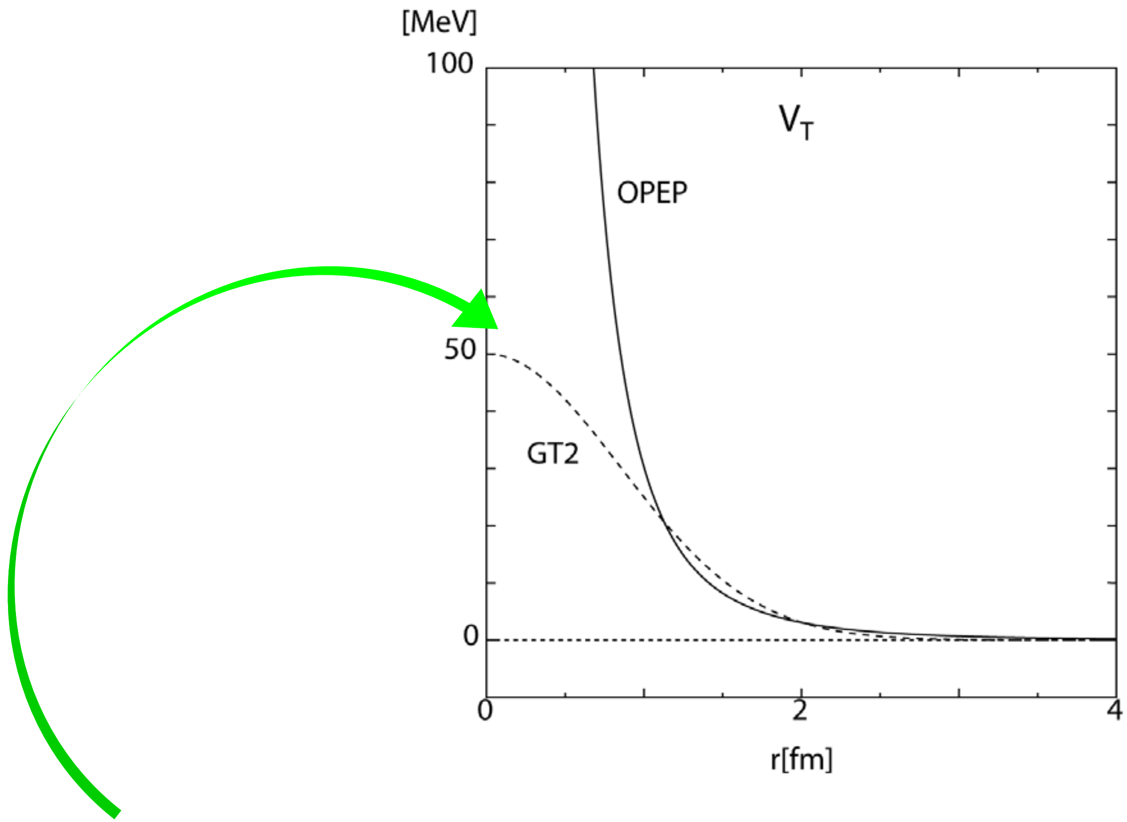
Tensor interaction is added

All parameters are readjusted

Nuclear matter properties reproduced with improvement of imcompressibility

Gogny-Tokyo interaction - 2 (GT2)

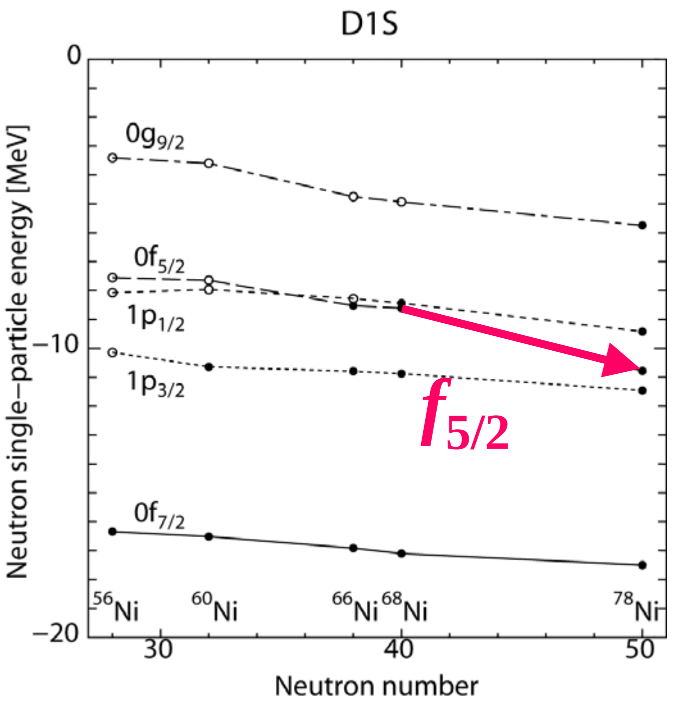
Tensor interaction actually used



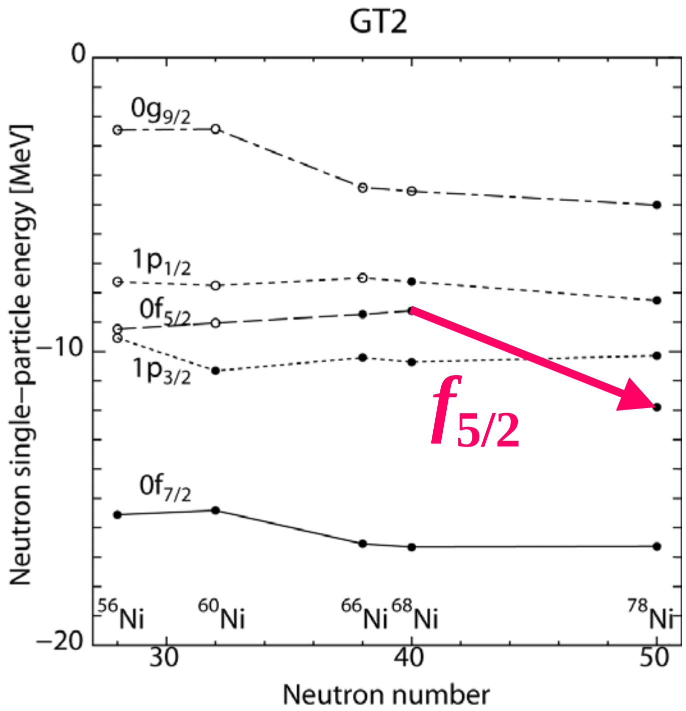
Regularized for short distance

Neutron effective single-particle energies of exotic Ni isotopes

Original (D1S)

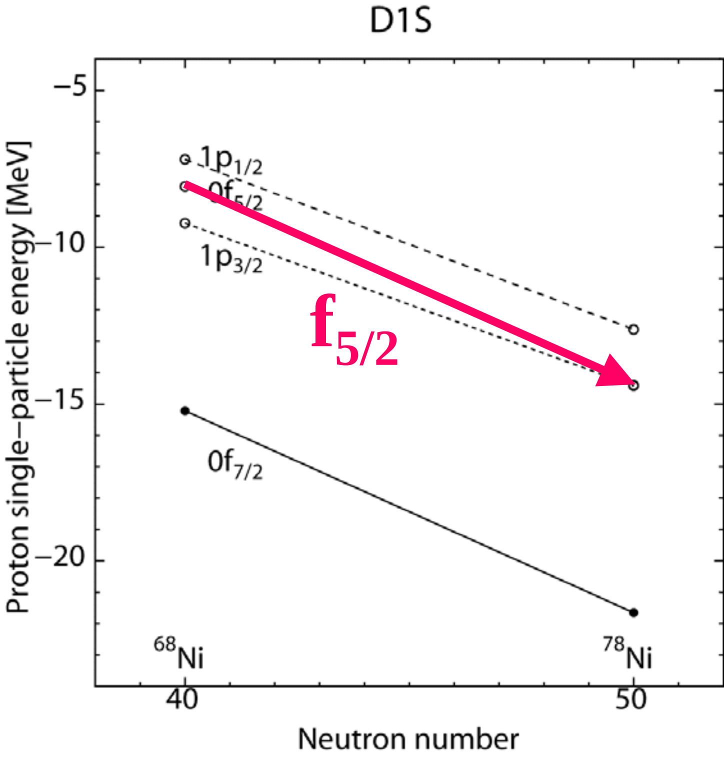


GT2 (incl. tensor)

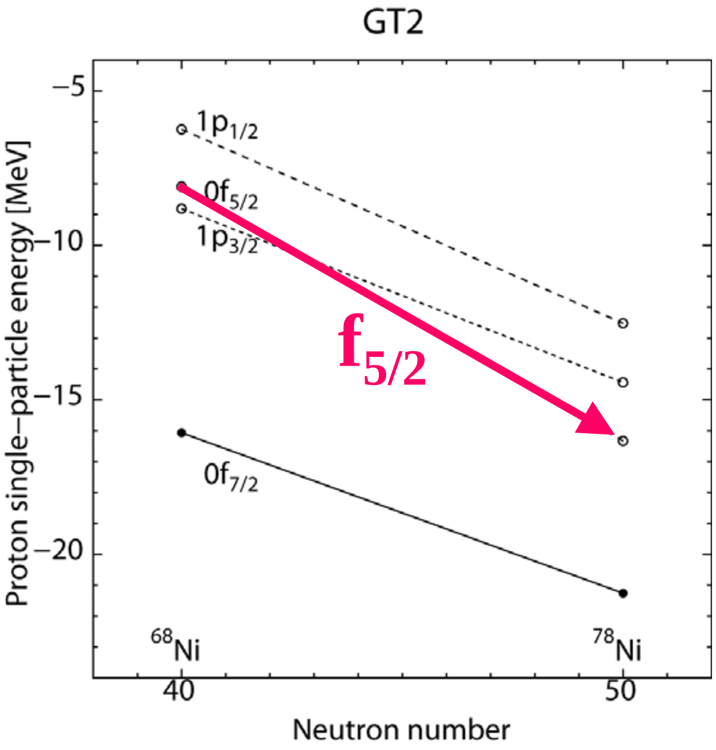


Proton effective single-particle energies of exotic Ni isotopes

Original (D1S)



GT2 (incl. tensor)



Summary

Shell evolution due to spin-isospin interactions

Tensor interaction (long range)

drives $j_>$ or $j_<$ levels in a specific way

This is not necessarily a change of spin-orbit splitting.

is the dominant origin of shell evolution

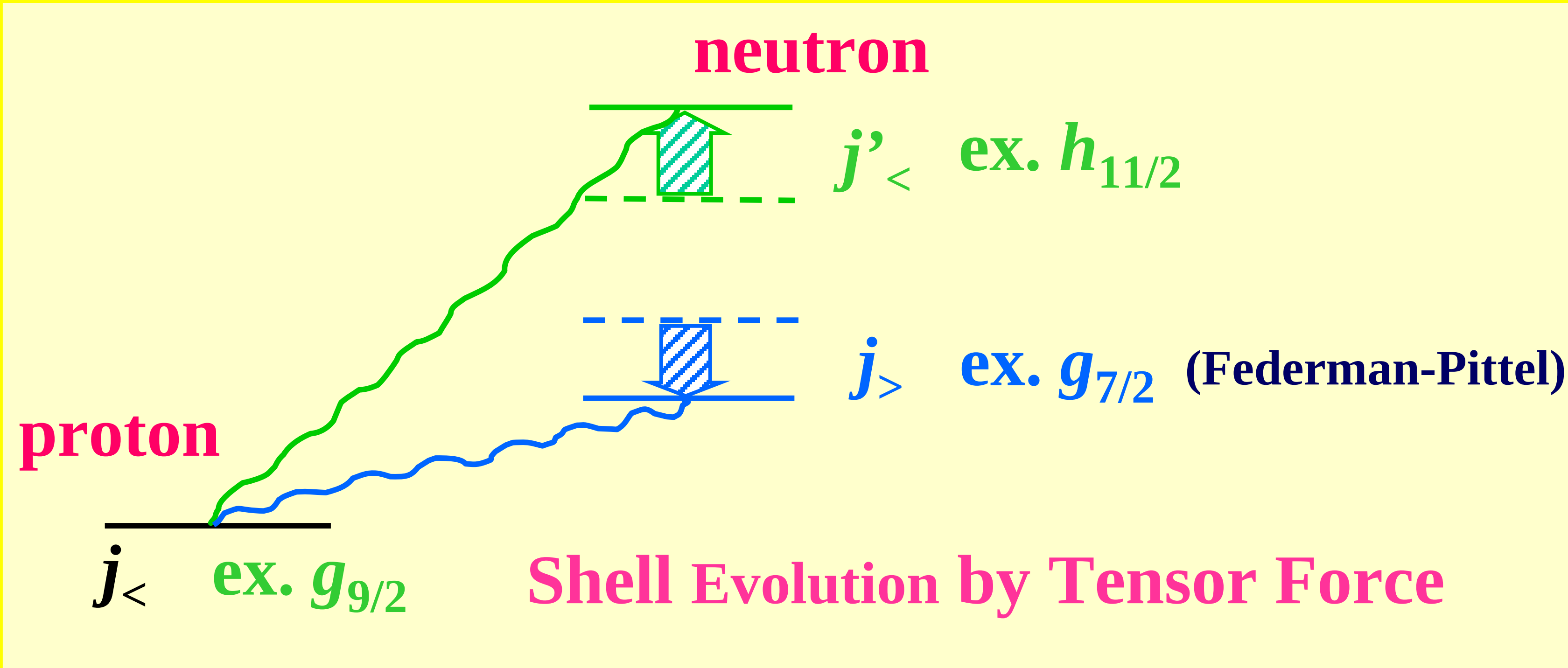
produces effects of similar magnitude to *neutron skin* (weakening of *ls* splitting)

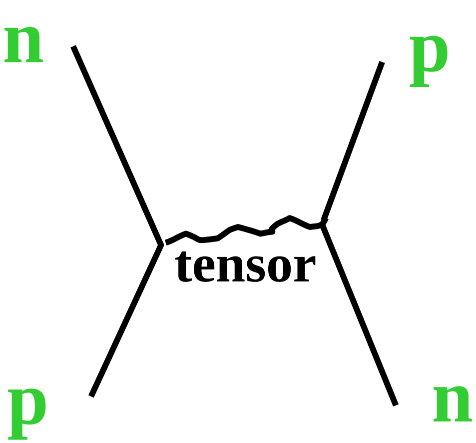
2-body *LS* interaction (short range)

special cases (*e.g.* between *s* and *p*)

carbon-oxygen $d_{5/2}$-$s_{1/2}$ inversion (same mechanism as ls splitting)

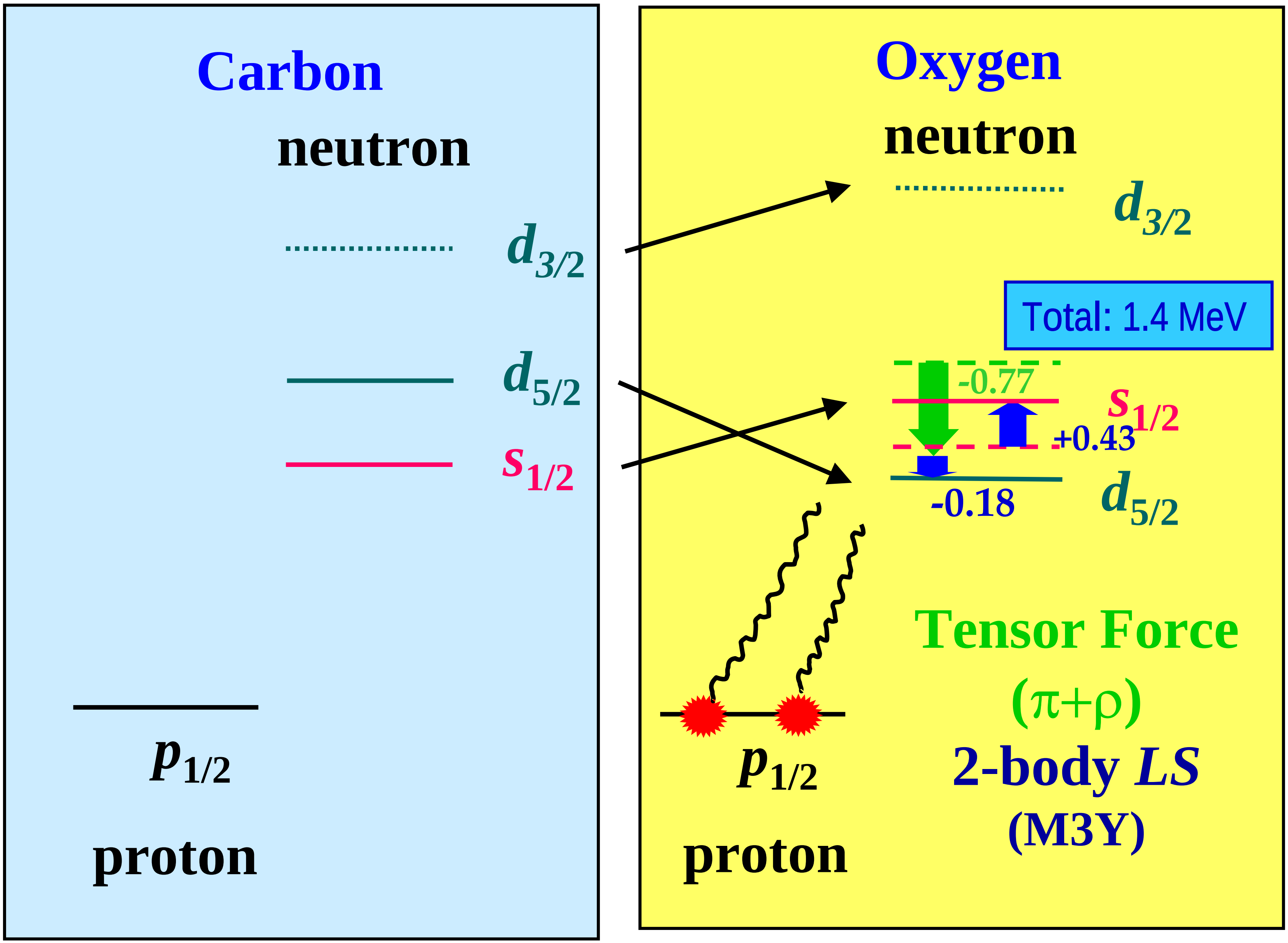
➡ Structure of exotic nuclei in many respects


neutron
j'< ex. h11/2
j> ex. g7/2 (Federman-Pittel)
proton
j< ex. g9/2
Shell Evolution by Tensor Force


n
p
tensor
p
n


exchange process

observed change of $d_{5/2}$-$s_{1/2}$: 1.6 MeV



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